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Transport Canada / Transports Canada
Development / Développement

TP 3933E

Superconductive Energy Storage for Trains

Summary Report

Prepared for the
Transportation
Development Centre
Transport Canada

March 1982

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CIGGT Project No. PRO-940

CIGGT Report No. 80-14
TDC Report No. TP-3933E

EXECUTIVE SUMMARY

SUPERCONDUCTIVE ENERGY STORAGE FOR TRAINS

A.R. Eastham
G.W. English
D.M. Pringle
P.R. Austin

This study was conducted by CIGGT for the Transportation Development Centre of Transport Canada under Service Contract No. 4200.

Canadian Institute of Guided Ground Transport
Queen's University, Kingston, Ontario
K7L 3N6

March 1982

ACKNOWLEDGEMENTS

We would like to thank Mr. P.L. Eggleton, Executive Director of TDC, for suggesting this project; Mr. C.A. Versailles, Project Officer at TDC, for his interest and guidance in the development of the technical work and economic evaluation; Prof. D.L. Atherton, Physics Department at Queen's University, for his interest and advice in magnet design and cryogenics, and Dr. G.E. Dawson and P.C. Sen for their advice and assistance on the power aspects of the superconductive wayside energy storage system.

This report resulted from research conducted through the Canadian Institute of Guided Ground Transport. The report represents the views of the authors and does not necessarily have the endorsement of the University or the other participating organizations.

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REPORT DOCUMENTATION FORM

1. Transport Canada Report No.	2. TDC Project No.	3. Recipient's Catalogue No.
TP 3933E	4200	

4. Title and Subtitle	5. Report Date
SUPERCONDUCTIVE ENERGY STORAGE FOR TRAINS Executive Summary	March 1982
	6. Performing Organization Report No. 80-14
7. Author(s) A.R. Eastham, G.W. English, D.M. Pringle, P.R. Austin	8. Transport Canada File No. D1465-313_ 3/4
9. Performing Organization Name and Address Canadian Institute of Guided Ground Transport (CIGGT) Queen's University Kingston, Ontario K7L 3N6	10. DSS File No.
	11. DSS or Transport Canada Contract No 4200
12. Sponsoring Agency Name and Address Transportation Development Centre, Transport Canada 1000 Sherbrooke St. West, Box 549, Place de l'aviation Montreal, Quebec H3A 2R3	13. Type of Report and Period Covered Summary, May 80/April 81
	14. Sponsoring Agency Code PRO-940
15. Supplementary Notes	16. TDC Project Officer C.A. Versailles

17. Abstract

This study was commissioned to assess the technical and economic feasibility of a superconductive wayside energy storage system (SWESS) for Canadian railways. A comparison was also made with the flywheel WESS alternative previously evaluated by the Garrett Corporation. At the temperature of liquid helium, certain materials like niobium-titanium have special electrical properties. The resistivity drops to zero and a short circuited coil can thus sustain a very high current and flux density for indefinite periods of time. It then becomes possible to store high levels of energy without losses by varying the current and flux. Such a concept opens up interesting possibilities for storing train braking energy for several hours pending an energy demand from another train. A 10 MW SWESS system was considered for implementation on the Cartier Railway Company and the Quebec North Shore and Labrador Railway Company. A simple solenoid geometry and a 4.2 K pool-boiling refrigeration system were selected. It was determined that the SWESS coil would be much larger than any yet built, but considerably smaller than the coils proposed in other studies for utility load levelling. The technical designs of magnetic, cryogenic and electrical equipment were pursued in sufficient detail to provide credence to the cost estimates. While the superconductive system is technically feasible, it was concluded that the low foreseeable return on investment is likely to preclude further development of the SWESS concept.

18. Key Words	19. Distribution Statement
Energy storage WAYSIDE Superconducting coils Railway electrification	Full report available from CIGGT on request

20. Security Classification (of this report)	21. Security Classification (of this page)	22. No. of Pages	23. Price
NIL	NIL	23	

TDC/CDT 79 006

FORMULE DE DOCUMENTATION POUR RAPPORT

1. N° du rapport Transports Canada	2. N° de l'étude — CDT	3. N° de catalogue du destinataire
TP 3933E	4200	

4. Titre et sous-titre	5. Date du rapport
SUPERCONDUCTIVE ENERGY STORAGE FOR TRAINS Executive Summary	Mars 1982
	6. N° du rapport de l'organisme exécutant 80-14
7. Auteur(s)	8. N° de dossier Transports Canada
A.R. Eastham, G.W.English, D.M. Pringle, P.R. Austin	D1465-313
9. Nom et adresse de l'organisme exécutant	10. N° de dossier — ASC
Canadian Institute of Guided Ground Transport (CIGGT) Université Queen Kingston, Ontario K7L 3N6	11. N° de contrat — ASC ou Transports Canada 4200
12. Nom et adresse de l'organisme parrain	13. Genre de rapport et période visée
Centre de développement des transports (CDT) Transports Canada 1000, rue Sherbrooke ouest, C.P. 549, Place de l'aviation Montréal, Québec H3A 2R3	Sommaire, Mai 80/Avril 81
	14. Code de l'organisme parrain PRO-940
15. Remarques additionnelles	16. Agent de projet — CDT C.A. Versailles

17. Résumé

Le mandat de cette étude consistait à évaluer les faisabilités technique et économique d'un système supraconducteur de stockage d'énergie en bordure de voie (SWESS) pour les chemins de fer canadiens. Cette étude a aussi comparé le système de stockage à volant (WESS) déjà évalué par la Garrett Corporation. Certains métaux, tel le niobium-titane, possèdent des propriétés électriques spéciales lorsqu'ils sont portés à la température de l'hélium liquide. Leur résistivité descent alors à zéro et une bobine au ni-ti court-circuitée peut maintenir un courant élevé et un flux magnétique intense durant une période indéfinie de temps. Il devient alors possible d'emmagasiner de hautes teneurs d'énergie sans perte par la variation du courant et du flux. Un tel concept ouvre d'intéressantes possibilités d'emmagasiner durant plusieurs heures l'énergie de freinage d'un train jusqu'à une demande d'énergie d'un autre train. Un système de 10 MW a été envisagé pour mise en application à la Compagnie de Chemin de Fer Cartier et à la Quebec North Shore and Labrador. On a choisi une géométrie simple en solénoide et un système de refroidissement à l'hélium en état d'ébullition à 4.2° kelvin. Il a été constaté que la bobine SWESS serait beaucoup plus volumineuse que toute autre déjà fabriquée, et notablement plus petite que les bobines suggérées dans d'autres études sur l'égalisation des charges d'alimentation. Les études techniques du matériel magnétique, cryogénique et électrique ont été poursuivies avec assez de précision pour supporter l'évaluation des coûts. Bien que le système supraconducteur soit techniquement faisable, l'étude conclut que la faible rentabilité de la mise de fonds écartera possiblement le développement futur du concept SWESS

18. Mots-clés	19. Diffusion
Stockage d'énergie en bordure de voie. Bobines supraconductrices. Electrification ferroviaire.	Rapport complet disponible auprès de CIGGT

20. Classification de sécurité (de ce rapport)	21. Classification de sécurité (de cette page)	22. Nombre de pages	23. Prix
AUCUNE	AUCUNE	23	

CDT/TDC 79-005

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1. INTRODUCTION

Increasing attention is being given to the energy efficiency of North American railway operations. As both Canadian and world prices of fossil fuels continue to rise, the cost of energy required to move people and freight is becoming an increasingly significant proportion of railway operating costs. The possible use of alternative fuels, such as hydrogen or natural gas, is therefore being explored, and the implementation of main line electrification is again the subject of technical and economic assessment.

The operating efficiency of trains would be substantially improved if at least part of the energy delivered for acceleration and for grade climbing could be reclaimed. Conventional diesel electric locomotives use a combination of dynamic and friction braking, both of which dissipate the potential and kinetic energy as heat. Reclamation of this energy requires regenerative braking and a means of either storing it on board or of transferring it to a track-side power distribution system. The former option could be achieved by inertial storage, i.e. by a flywheel coupled either electrically or mechanically to the locomotive drive. The latter option would require line electrification.

The magnitude of braking energy available from a loaded freight train makes the size and weight of a flywheel prohibitively high for on-board installation. Mobile inertial storage of braking energy is most appropriate for comparatively lightweight vehicles operating under frequent stop/go conditions, i.e. for urban transit systems[1]. buses and delivery vehicles. For railways operations, regenerative braking must be considered in association with electrification. The braking energy of one train can then be made available to other trains, or indeed to any other load on the electrical distribution system. However, simple regeneration back into the wayside line may not result in any significant reduction in the cost of energy to the railway. Even if the utility lines were receptive to intermittent regeneration, the railway would get little credit for energy returned. The nature of the load presented to the utility by electrified trains results in irregular high peak power demands, and the tariff structure is such that the electricity billing is biased toward peak power demand rather than to energy drawn at the metering point.

2. WAYSIDE ENERGY STORAGE

The most effective way in which the energy costs of an electrified railway could be reduced would be to limit the peak power demand. This could be achieved by storing the regenerative braking energy of trains for subsequent delivery to trains requiring high power for acceleration or grade climbing. This "peak shaving" operation with respect to the metering points would require a wayside energy storage system (WESS) coupled to the track third rail or catenary.

Regenerative braking in association with wayside energy storage offers the potential of improved energy efficiency and lower

operating costs for electrified transportation systems. The Garrett Corporation has conducted extensive studies to determine the practicality and viability of wayside energy storage for freight railway applications, under contract to the U.S. Department of Transportation.[2] Garrett evaluated only those energy storage technologies which were perceived to be close to state-of-the-art, namely;

- conventional and advanced lead-acid batteries
- advanced high energy/power density batteries (Na-S,Ni-Zn,etc.)
- pumped hydro storage
- compressed air storage
- regeneration to the utility
- flywheels.

Inductive energy storage, using superconducting magnets, was not (in 1978) considered as an option for a railway WESS facility.

As a result of their studies, Garrett concluded that large wayside flywheels, coupled to a high voltage (25-50 kV) a.c. catenary through a synchronous machine and power semiconductor converter, as shown schematically in Figure 1, would provide the most feasible means of recuperating braking energy from trains. An economic assessment indicated that the deployment of WESS on specific routes in the United States would lead to annual return-on-investments (ROI's) in the range of 17 to 27 per cent.

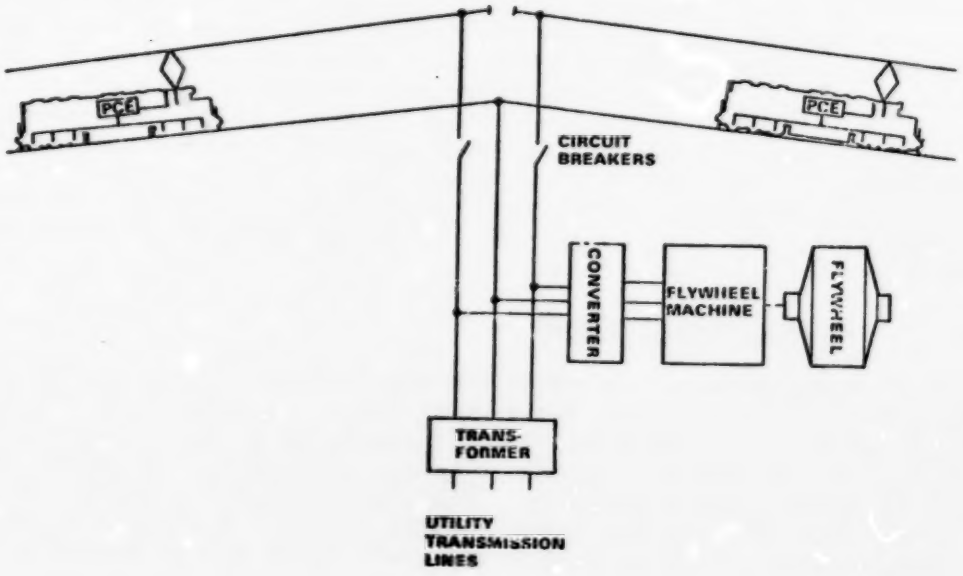

Figure 1 The flywheel WESS regeneration system (from reference 2)

3. CANADIAN APPLICATIONS FOR WESS

Throughout the Canadian railway system, there are a number of grade sections at which it could prove beneficial to install a wayside energy storage facility in association with railway electrification. Those long down-grades carrying loaded unit freight trains offer the greatest potential for improvements in energy efficiency due to WESS implementation. In particular, the grades through the Rocky Mountains and on some of the lines operated by mining companies are particularly appropriate sites for an assessment of the techno-economic feasibility of WESS in Canada.

Transport Canada monitored the work on wayside energy storage in the United States and saw equivalent Canadian applications for this technology. At the conclusion of the work for the U.S.D.O.T., Garrett was awarded a contract to study the application of the flywheel WESS concept to Canadian railways[3].

The two iron ore railways, the Quebec North Shore and Labrador (QNS&L) and the Cartier Railway Company (CRC), were considered to be particularly appropriate for consideration of WESS implementation. Both companies operate heavy freight trains down long grades from inland ore bodies to terminal facilities on the St. Lawrence River. The location of these railways is shown in Figure 2.

Garrett used their Train Performance Calculator[2] to provide energy consumption and braking data for typical consists on the specific terrain of the QNS&L and CRC. The model allowed sections of significant braking on these railways to be identified. The grades on five of these sections (four on the CRC and one on the QNS&L), were considered to be sufficiently long and severe to make these sectors potential sites for WESS implementation.

Rather than conducting design studies for the flywheel and converter at each potential site, Garrett selected a set of baseline specifications and developed the conceptual design and unit costs for a typical flywheel WESS station. The specifications are given in Table 1. Economic assessment indicated that return-on-investments of 17.6% and 7.3% could be achieved for the CRC and QNS&L railways, respectively.

TABLE 1 BASELINE WESS SPECIFICATIONS

Total energy storage capacity (at 100% rated current)	7.33 MW.h (26.4 GJ)
Usable energy storage (to 50% rated current)	5.5 MW.h (19.8 GJ)
Peak power level	10 MW
Operating life with minimum maintenance	30 years

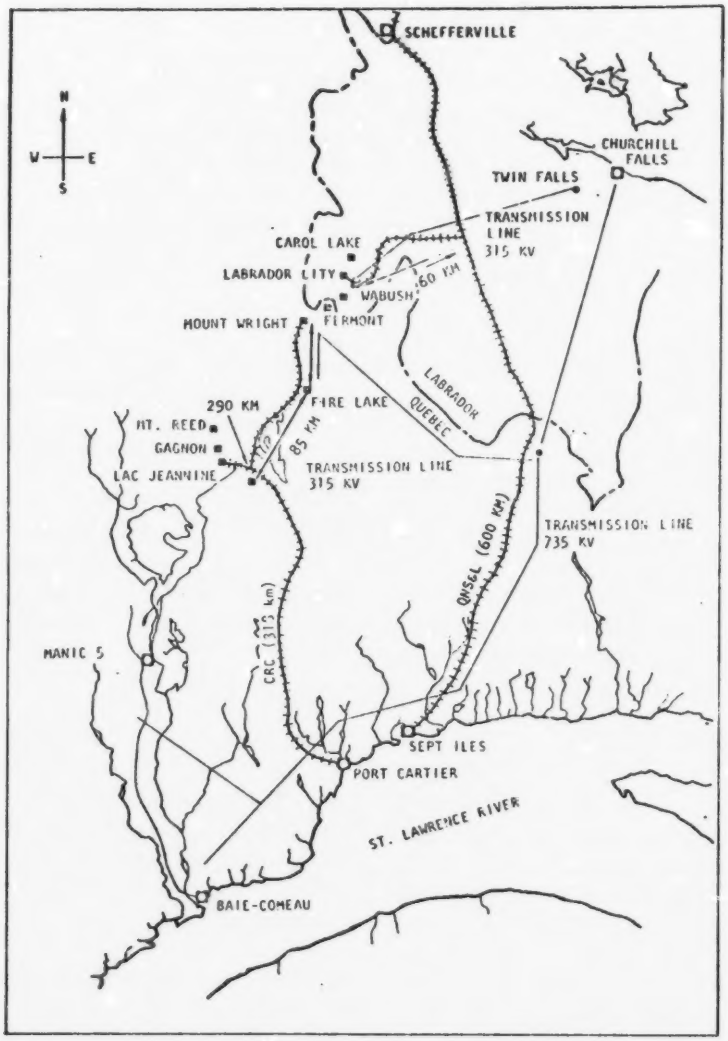

Figure 2 Location of the Cartier Railway Company and Quebec North Shore and Labrador railways (from reference 2)

As a result of the Garrett studies [2,3], it was realized that the braking energy of a loaded freight train was of such a magnitude that a WESS flywheel would have to be many times larger than any yet built. It was evident that an extensive research, development and demonstration program would be required to make flywheel WESS an engineering reality. However, the WESS concept itself was considered sufficiently attractive to warrant investigation of other advanced storage technologies which might become technically and economically viable and competitive with the flywheel system. The prime contender is then inductive energy storage using a superconducting magnet.

The Transportation Development Centre of Transport Canada awarded a contract to the authors to assess the technical and economic feasibility of a superconducting magnet wayside energy storage system (SM WESS), designed to the same baseline specifications as was used by Garrett (see Table 1). A report of this work[4] is presented here.

4. THE SM WESS CONCEPT

The flywheel WESS regeneration system proposed by Garrett [2,3] has been shown in Figure 1. Application of magnetic energy storage would require the flywheel, direct-coupled synchronous machine and part of the power conditioner to be replaced by a superconducting magnet and a transformer, as shown in Figure 3.

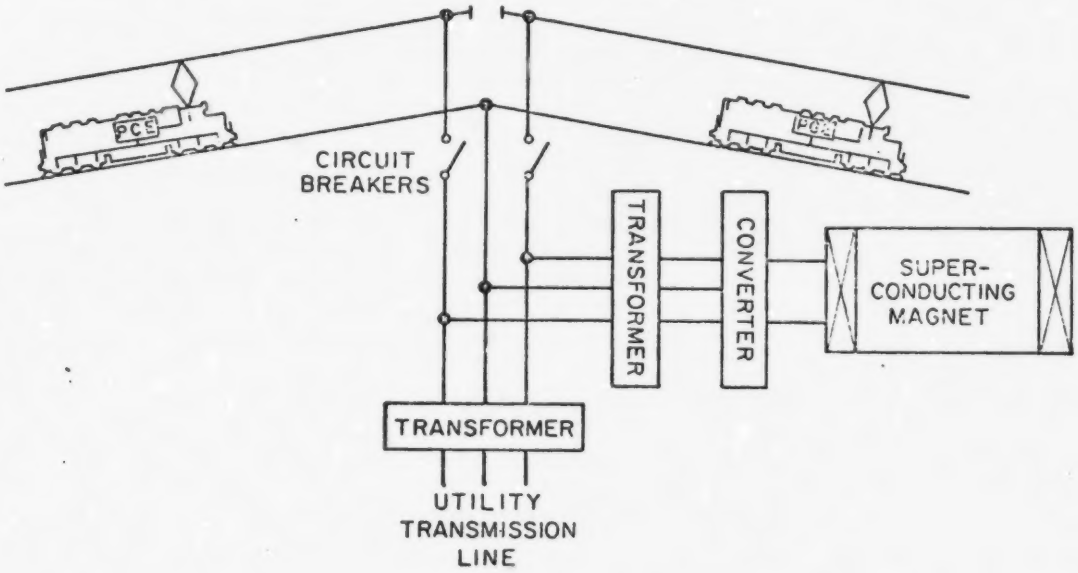

Figure 3 The superconducting magnet WESS regeneration system

The design concept of the SM WESS is shown in more detail in Figure 4. Apart from the storage facility and its converter, the power system is identical to that for an electrified railway. The 50 kV (or 25 kV) single-phase a.c. feeds to the two adjacent catenary sections are provided by the three-wire output of a transformer bank connected such as to minimize phase unbalance in the power drawn from the utility.

As the superconducting magnet is a comparatively low-voltage, high-current device, it is necessary to interpose a single-phase, step-down transformer between the catenary and the energy storage converter.

The two single-phase thyristor power conditioners can be controlled to allow the superconducting magnet either to store the regenerative

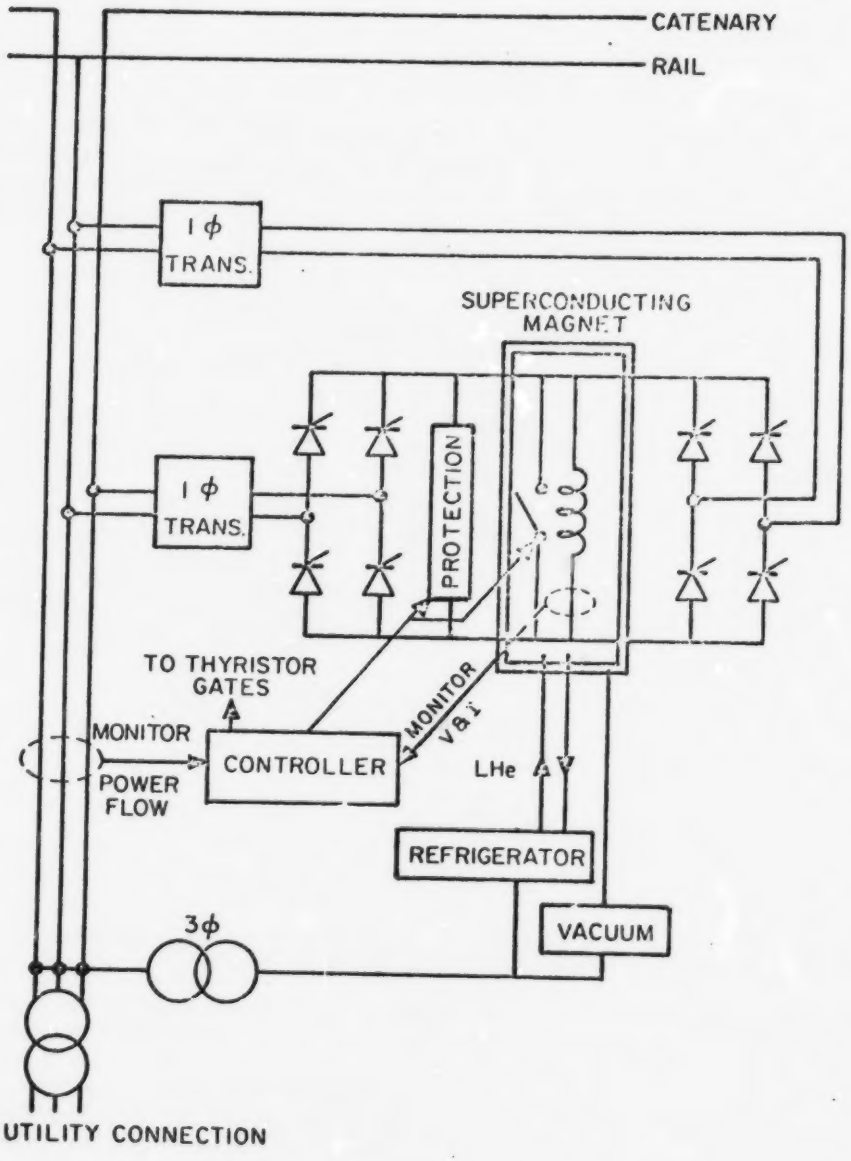

Figure 4 A schematic of the power and control circuits for SM WESS

braking energy of a descending train or to deliver energy to an ascending train. The magnet would be charged if a regenerative power flow to the utility was detected (or if the stored energy dropped below a specified level), and the energy would be drawn from the magnet when the power demand from the utility exceeded a certain level. The WESS therefore acts as a peak shaver with respect to the utility connection.

5. SUPERCONDUCTING MAGNET TECHNOLOGY AND ENERGY STORAGE

The discovery of type II superconducting materials, such as the alloy NbTi and the intermetallic compound Nb_3Sn, in the early sixties, and the subsequent understanding of the physical mechanisms for high field superconductivity led to the development of superconductors capable of stable operation at high current density in magnetic fields up to 15 Tesla. Over the past decade, superconductors have emerged from the research and development laboratories, and superconducting magnets are now being used or are being proposed for a wide range of industrial applications.

The range of applications of superconducting coils, grouped according to their relative magnetic energy storage, is given in Table 2. A great deal of engineering experience has been gained on systems in the intermediate energy range and on bubble chamber coils in the high energy range. As a result, superconducting coils are being accepted and operated in fields as diverse as geophysical explorations, ore beneficiation, medical diagnostics, fundamental particle research and nuclear engineering.

As an energy storage device, a superconducting coil can be considered as a large zero-resistance air-cored inductor, L, carrying a dc current, I. The total energy, W, is given by;

$$W = \int \frac{B^2}{2\mu_0} \, dV = \frac{1}{2} L I^2 \quad \text{joules}$$

where the volume integral is taken over all space, of permeability μ_0, having finite flux density B.

A major potential application for superconducting magnets is for diurnal load levelling or peak shaving in power systems. The utilities in a number of countries now make use of hydro pumped storage for this purpose. The spare night-time generation capacity is used to drive turbines which pump water to elevated level reservoirs. During daytime peak load periods, the turbines are reversed and drive generators to feed electrical energy back into the distribution system. The largest pumped storage unit in the U.S., at Ludington, Michigan, has a capacity of 8.3 GW hr, and facilities of comparable magnitude are in or near operation in Japan and Great Britain. This mode of energy storage, while having a round-trip efficiency typically of only 65 per cent and while geographically limited, provides valuable load levelling service.

The alternative idea of storing electrical energy in very large superconducting coils is, at first sight, a very attractive one. A

TABLE 2 APPLICATIONS OF SUPERCONDUCTING COILS

Scale	Stored Energy (joules)	Application	State of Development
Small	$<10^4$	.Research magnets (as high field sources, for NMR spectroscopy, etc.) .Geophysical prospecting	in operation
Intermediate	10^4-10^7	.Medical diagnostics .High energy physics research (beam bending magnets, particle accelerators, synchrotrons, etc.) .Ore beneficiation .Magnetic suspension of high speed trains .Magnetic filtration .Superconducting generators and motors (ship propulsion, etc.) .Electromagnetic launchers .VAR compensation in power systems	design studies or under construction
Large	10^7-10^{10}	.MHD generators .Bubble chamber magnets .Power system stabilizers	proposed
Huge	$> 10^{10}$	.Fusion power reactors .Energy storage .Interstellar propulsion	

coil can be connected in parallel with the utility distribution system through a low loss power conditioning unit, and energy is stored directly in electromagnetic form without intermediate lossy conversions. Proposals for diurnal load levelling using 1-10 GW hr superconductive energy storage magnets date from the early seventies, and extensive feasibility and design studies have been conducted by teams at the University of Wisconsin and at the Los Alamos Scientific Laboratory in the U.S. and by various laboratories in Japan (see, for example, references 5-10).

The present state of superconductive energy storage technology can be gauged by reference to Figure 5. The magnitude of energy stored by various superconducting coils is shown as a function of their year of operation. In 1977, Powell [11] reported that there were only 20 superconducting magnets in the world with a storage capacity in excess of 1 MJ, most of which was designed for particle physics or nuclear fusion research rather than for energy storage. The two

largest superconducting coils, having storage capacities of 400 MJ and 800 MJ respectively, were operated with bubble chambers at the National Argonne Laboratory in the U.S. and at CERN in Switzerland. In 1981, it can be considered that coils of storage capacity up to 100 MJ and perhaps up to 1000 MJ could be designed and built by use of techniques which have been demonstrated and which are widely accepted in the superconducting magnet industry.

A SM WESS coil, meeting the specifications in Table 1, must have a total storage capacity of 7.33 MW hr. or 26,400 MJ. This is evidently at least a factor of thirty above that which can be considered present state-of-the-art. However, the detailed predesign proposals of the Wisconsin and LASL groups for diurnal load levelling applications involve coils with storage capacity in the range 1-10 GW hr., i.e. a factor 10^2-10^3 higher than for the SM WESS coil. While the SM WESS coil is much larger than any yet built or planned, it is in an energy range that is considered to be technically feasible. As will be discussed, the superconductor itself is fairly standard and cables of the required ampacity have been fabricated and tested. The major design problems for a coil of the SM WESS size are concerned with force transfer, differential thermal contraction, stress and strain under cyclic loading, and protection.

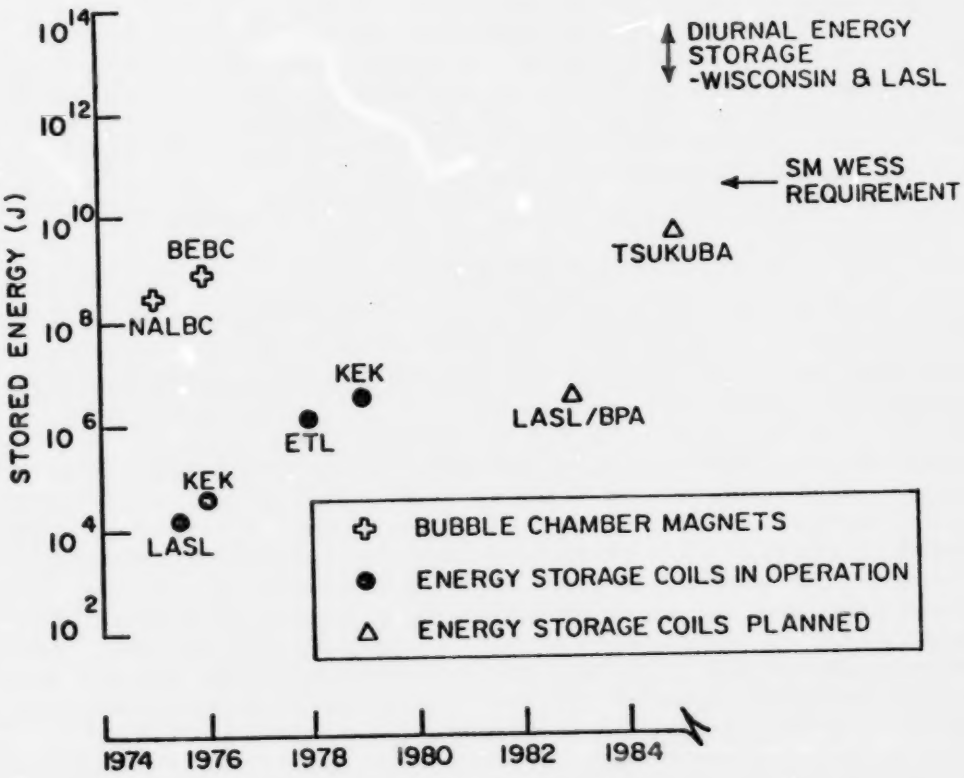

Figure 5 The stored energy of superconducting magnets.

6. THE SM WESS DESIGN

A conceptual design study has been conducted to determine the technical feasibility and to identify and cost the principal elements (coil, cryogenic containment, power conditioners and control system) of a superconducting wayside energy storage facility to meet the specifications given in Table 1. It cannot be claimed that an optimal design has been achieved for each subsystem. Rather, an attempt was made to carry the technical work to sufficient depth to provide credible cost estimates for the economic assessment of SM WESS.

6.1 Coil Configuration

The solenoid is the simplest coil configuration from the points-of-view of construction and force containment, and makes the most effective use of superconductor in terms of stored energy per unit ampere-meter of conductor[12].

The undesirable feature of the solenoid is its large fringing field. Early investigators of magnetic energy storage systems therefore considered coil geometries which enclosed most of the field within their windings (e.g. toroid, dipole or multiple solenoid configurations). As more detailed studies progressed, it became evident that there would be major cost penalties associated with the design complexity of these coils.

In order to give SM WESS its best chance at economic viability, it is necessary to select a coil configuration which minimizes the capital cost of superconductor and which is structurally as simple as possible. The simple solenoid is therefore selected, and it is assumed that the SM WESS facility can be located away from any equipment likely to be affected by the appreciable fringing fields.

6.2 Peak Field, Voltage and Current

The SM WESS magnet must be capable of storing 7.33 MW.hr (2.64×10^{10} joules) at a peak power level of 10 MW. The design of the solenoidal coil was begun by the selection of peak winding field, voltage and current.

Initial designs were conducted for peak fields of 5 Tesla and 10 Tesla, considered to be appropriate for NbTi and Nb_3Sn superconductors, respectively. Unit cost estimates for superconducting materials were obtained from Airco Co.[13] and from Intermagnetics General Corp.[14] and it was determined that the cost of superconductor for an Nb_3Sn coil operating at a peak field of 10 Tesla would be approximately 2.5 times that for an NbTi coil operating at a peak field of 5 Tesla. NbTi was therefore selected as the material for the SM WESS coil, and the peak field was specified to be 5 Tesla.

The SM WESS is designed to have a usable stored energy of 5.5 MW.hr when operating between 100 per cent and 50 per cent of rated

current. Maximum voltage occurs when the coil is charging or discharging at rated power and at 50 per cent of rated current. Current design practice for large superconductive coils is to use a high-current conductor. This tends to simplify the problem of force containment and minimizes the cost of magnet construction. An operating current range of 7.5-15 kA was therefore selected, requiring a maximum coil voltage of 1.33 kV. Conductors with this current and voltage rating are well within the current state-of-the-technology.

For a maximum current of 15 kA, the stored energy specification allows the required coil inductance to be identified as 235 Henries.

6.3 Solenoid Optimization

Recognizing that the capital cost of superconductors is likely to be a dominant component of the total system cost, an attempt was made to seek a solenoid geometry which minimizes the amount of superconductor required.

Solenoids with various winding cross-sections were considered. For a given aspect ratio (winding height x width), an iterative design procedure was adopted, using the Working Formulas and Tables for Inductance Calculations by Grover[15] and the Universal Tables for Magnetic Fields of Distributed Circular Currents by Hart[16], to determine the mean radius and the number of turns that produced the required inductance and which limited the maximum field to 5 Tesla. Figure 6 shows coil geometries which simultaneously meet the stored energy and peak field specifications. These coils are large; up to 50 metres in radius or 10 metres in height.

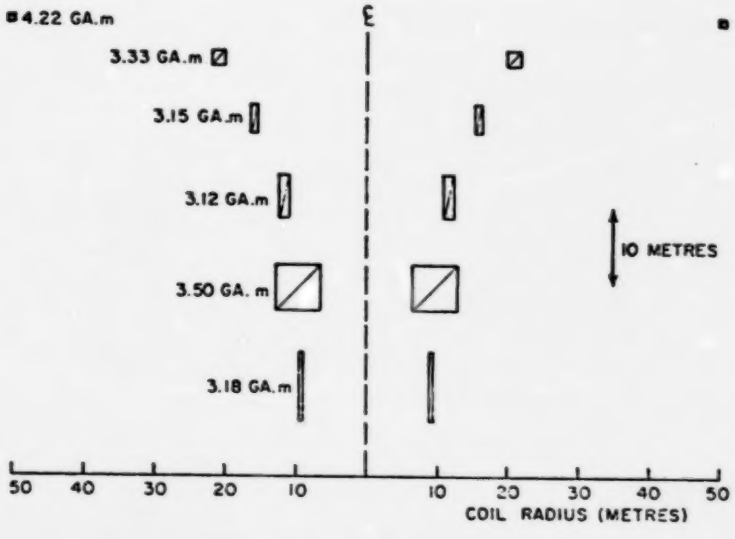

Figure 6 5 Tesla peak field solenoid geometries. The quantity of superconductor required for a maximum stored energy of 2.64×10^9 joules is shown in terms of 10^9 ampere metres.

From the winding optimization studies, it became evident that, for a given maximum stored energy, the quantity of superconductor required is rather insensitive to coil geometry. The latter can therefore be selected from considerations of ease of construction, force containment, thermal losses and electrical interface. Of these factors, force containment is likely to be the most important. It is necessary to ensure that there is sufficient space within the coil section for coolant channels, for insulation and for structural integrity components. A further iteration was therefore carried out to identify a winding cross-section that would meet these requirements. The selected coil geometry together with other design parameters for the SM WESS coil are given in Table 3.

TABLE 3 DESIGN PARAMETERS OF SM WESS COIL

Maximum stored energy	2.64×10^{10} joules
Maximum power	10 MW
Maximum current	15 kA
Minimum current	7.5 kA
Maximum voltage	1.33 kV
Inductance	235 Henries
Number of turns	2,576
Peak field at windings	5 Tesla
Quantity of superconductor (at 15 kA)	3.04×10^{9} amp. metres
Ramp time (7.5 ⇐⇒ 15 kA)	approx. 30 minutes

Cross-section (not to scale):

6.4 Conductor

For a superconductive coil of the size required for SM WESS, the major design objectives must be:

(i) to seek a low-cost conductor

(ii) to ensure that the high capital investment in superconductor is protected, i.e. the conductor must be adiabatically stable under normal operation and cryogenically stable under fault conditions, and must be capable of safely absorbing the maximum stored energy in the coil in the event of a refrigeration failure.

Implementation of both adiabatic and cryogenic stabilization should ensure safe, reliable, long-term operation of the superconductive coil.

The maximum current selected for the coil conductor was 15 kA. In order to provide a margin of safety, a conductor with a critical current of 20 kA at 4.2 K is specified.

For application on the CRC or QNS&L railways, the SM WESS coil would be charged or discharged, i.e. ramped between 7.5 kA and 15 kA, over a time of order 30 minutes. [3,4] The rate of field change, dB/dt, experienced by the winding will be considerably lower than for most "pulsed" applications. After an extensive literature review, and after discussions with representatives of two superconducting material manufacturers, [13,14] it was determined that an aluminum-stabilized conductor of the type shown in Figure 7, modified to meet the selected SM WESS conductor specifications, would be as close to optimal, in terms of cost and losses, as can be identified at this time. This design was the result of a study for the conductor of a 10 MW.hr energy storage coil, conducted by Intermagnetics for LASL. [17] The conductor design is based on a near-term projection of the development of conductor material technology tested on smaller energy storage coils.

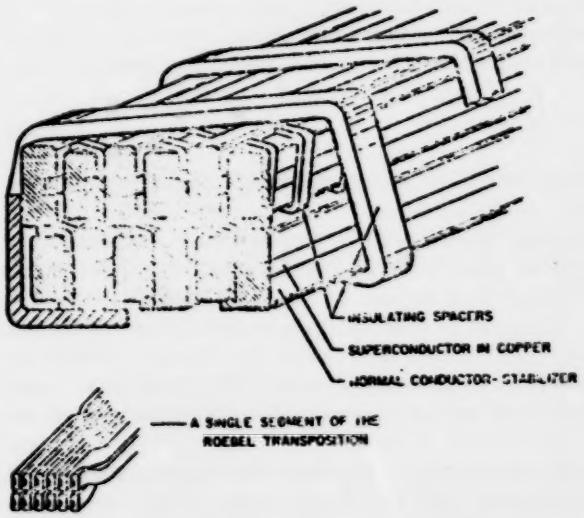

Figure 7 A possible design for the SM WESS coil conductor

The basic superconductor is a multifilament NbTi-Cu composite. This is bonded metallurgically into the stabilizer to form the sub-conductor. An insulating strip is then wrapped around alternate subconductors, and eight elements (for the SM WESS coil) are stacked together to form the cable. The overall conductor is held firmly together with an outer wrap of insulating strip. The cable must be transposed (using a Roebel transposition pattern) to minimize coupling losses, and the gaps between the insulating spaces must be sufficiently large (>0.5 mm) to allow bubble clearing under helium pool boiling conditions.

6.5 Force Containment

For very large (1-10 GW.hr) energy storage coils for utility diurnal load levelling applications, it has been shown by the Wisconsin and Los Alamos groups [5,7] that warm structure is economically essential. The radial expansive force must be carried from the windings, along epoxy-fiberglass struts, through the dewar walls to a competent rock face.

For the comparatively modest-sized coil for SM WESS, the capital cost will be dominated by the material and fabrication of the superconducting coil, rather than by the force transfer mechanism. The design complexity and novel nature of warm structure is therefore avoided and cold structure is proposed. The state-of-the-technology for force containment in large magnets is to use sufficient structure in or around the windings to take the radially outward force as hoop stress and the axial force as compressive stress. This technique is proposed for the SM WESS coil.

Two approaches may be used to determine the amount of structural material required. The first, advocated by the Wisconsin group[5], makes use of the virial theorem to calculate the minimum mechanical structure required to confine the magnetic field. The second approach determines the cross-sectional area of structure required to maintain the hoop and compressive stresses to some limiting value. The two methods yield consistent information about structural requirements.

An aluminum alloy with the appropriate heat treatment is stronger per unit weight and cheaper than stainless steel, and is the proposed structural material. For 6061 - T6 aluminum at 4.2K, the ultimate tensile stress is 83 kpsi (5.7×10^8 N/m^2), and a safe working stress is taken to be 30 kpsi(2×10^8 N/m^2). Computations based on the Wisconsin development of the virial theory[5] and on cross-section of structure required to limit the hoop stress to the above value gave a total structural requirement (to restrain both radial expansive and axial compressive forces) of 5×10^5 kg.

This structural material could not be located in one simply connected band around the winding; even with the slow ramp rate for the SM WESS application, the induced eddy current loss would be

intolerably high. A spiral 6061-T6 aluminum support co-wound with the conductor (see Figure 8) is therefore proposed.

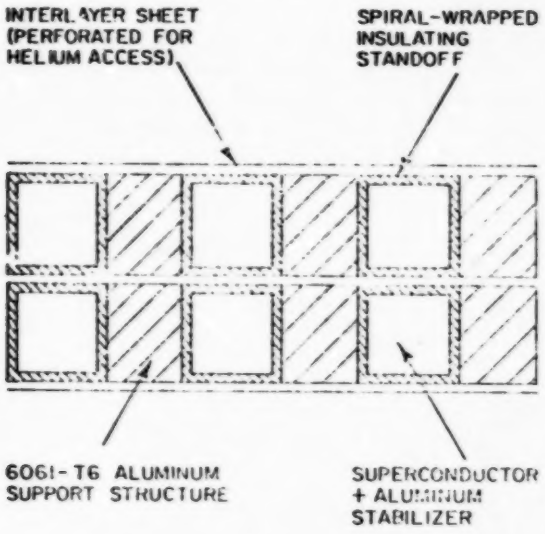

Figure 8 A section of the SM WESS coil winding

The SM WESS coil would be wound in 108 double-pancake sections, each with 24 turns. Each layer would be separated by a perforated sheet to allow helium access and bubble effusion from the windings. The coil could be supported by means of fibre-reinforced plastic bobbin and end plates. Additional spirally-wrapped anodized 6061-T6 aluminum strip would be wound around the outside of the coil to make up the remainder of the structure required to support radial expansive forces. The alternative of incorporating all the required structure in the winding would require the coil thickness to be increased from 0.50 m to 0.70 m. Axial compressive forces are taken adequately by the internal aluminum support structure.

6.6 Cryogenics

Two cryogenic modes were considered for SM WESS operation;

- pool boiling at 4.2-4.4 K, with effluent helium gas used to cool radiation shields and to reduce input lead losses.

- superfluid cooling at 1.8 - 2.0 K.

While the higher critical current density of NbTi at 2 K is attractive as a means of reducing the cost of superconductor, the more conventional pool boiling operation was selected for techno-economic evaluation of SM WESS.

A schematic of the dewar structure is shown in Figure 9. The simplest configuration is proposed, consisting of a top opening

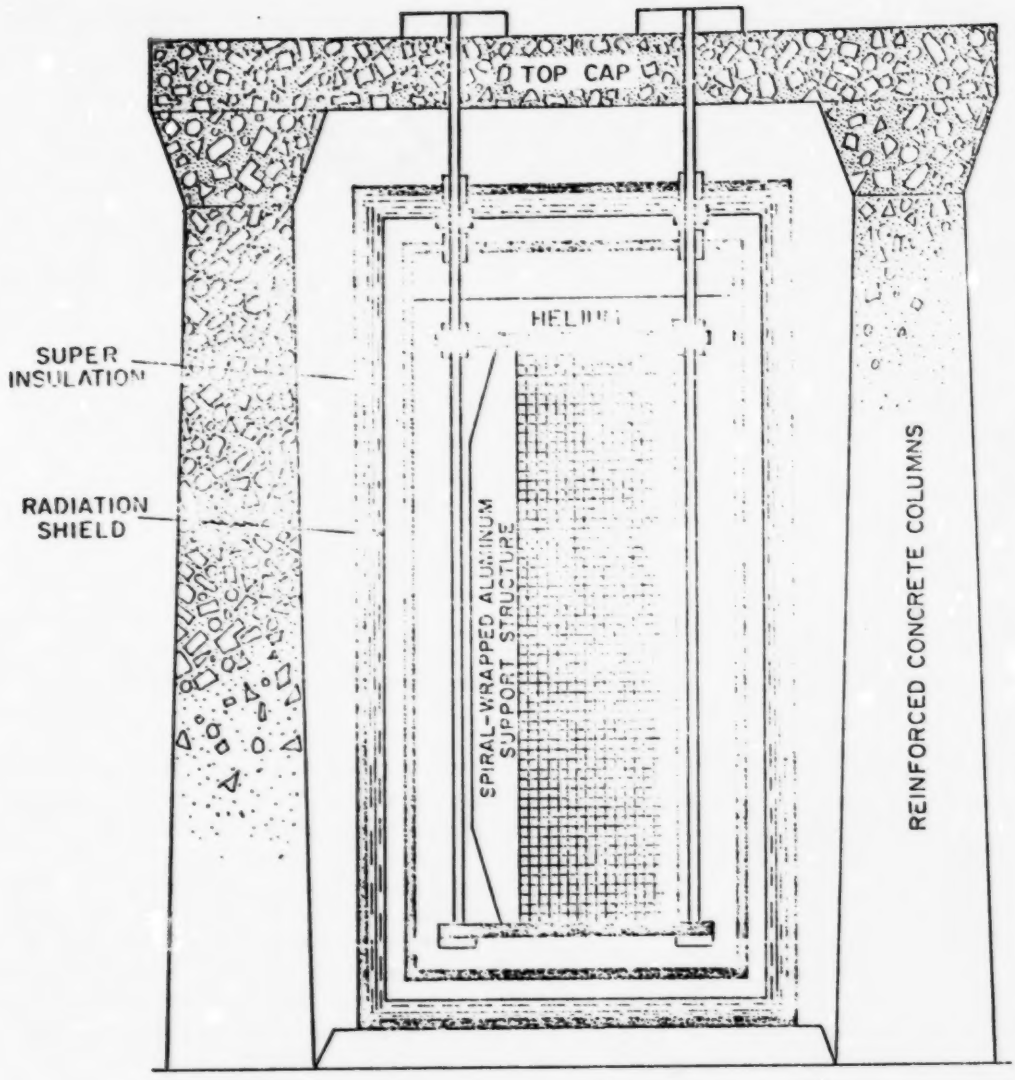

Figure 9 A schematic of the proposed SM WESS coil and dewar cross section (not to scale)

cylindrical vessel of liquid helium boiling at atmospheric pressure in which the magnet and dewar walls are suspended from a top cap.

The helium vessel must either incorporate an axial insulating link to cut the eddy current path if fabricated from stainless steel, or be constructed of non-conducting material such as fibre-reinforced-plastic. If the latter material is used, a wall thickness of 1.9 cm (3/4 in.) should be adequate.

The refrigeration requirements for the magnet were estimated by adding electromagnetic, mechanical, persistent mode switch,

conduction and radiation losses during rated charge/discharge conditions, while holding full charge and while holding half charge, as shown in Table 4.

TABLE 4 HEAT LOAD AT 4.2 K IN THE SM WESS MAGNET

	During 1/2 hour charge or discharge (watts)	While Holding Full Charge (watts)	While Holding Half Charge (watts)
Electromagnetic losses:			
Hysteresis	72	0	0
Eddy currents in matrix	negligible	0	0
Coupling	negligible	0	0
Self-field	2.2	0	0
Eddy currents in stabilizer	27	0	0
Joints	20	32	8
Eddy currents in reinforcement	8.6	0	0
Subtotal	130	32	8
Mechanical losses	20	0	0
Persistent mode switch	0	24	6
Conduction	45	35	35
Radiation	19	19	19
Total	214	110	68

The total estimated refrigeration requirement peaks at 214 watts during charging/discharging, and is a minimum at 68 watts while holding half charge. An overall average heat load is determined by assuming 8 half hour discharge periods, 8 full charge periods and 8 half hour charge periods per day. This duty cycle is appropriate to operation on the QNS&L and CRC railways.

The mean heat load is taken to be 100 watts, corresponding to a liquid helium boil-off rate of 146 litre/hour. In order to provide a safe margin of excess capacity and to allow some equipment redundancy to ensure continuous operation under routine maintenance and emergency repair conditions, a refrigeration plant consisting of two 100 litre/hour units is specified for SM WESS.

6.7 Electrical Interface

A schematic of the power and control circuits of the SM WESS has been shown in Figure 4. The system is capable of storing regenerative braking energy from or of delivering propulsion energy to locomotives under either of two 50 kV catenary sections separated by a phase break. Energy transfer across the phase break is accomplished by coupling the two single-phase lines to a d.c. link through 30:1 ratio step-down transformers. Back-to-back

phase-controlled thyristor bridges control power flow to the d.c. link, onto which the superconducting magnet energy store is connected.

During charging or discharging, the individual legs of the thyristor bridges carry the magnet current on a 50 per cent duty cycle. For a peak magnet current of 15 kA, the corresponding rms current of each leg is 10.6 kA. Allowing a margin for device reliability, the current rating of each thyristor leg is specified to be 16 kA. The peak voltage across each thyristor leg is equal to the peak line voltage, i.e. 2.36 kV. Again allowing a margin for device reliability, the voltage rating of each thyristor leg is specified to be 3.5 kV.

The required unit rating of 3.5 kV and 16 kA must be achieved by an appropriate combination of series and parallel devices, e.g. by 2 series x 10 parallel paths, for a total of 20 devices in each thyristor block of Figure 4. Balancing networks are required to ensure that the voltage and current loading is shared equally among the devices.

By monitoring the power flow at the utility, the superconductive coil current and voltage, and the liquid helium level in the storage vessel and in the magnet dewar, a controller must provide the appropriate signals to the power conditioner and to the refrigeration system to ensure effective utilization and safe operation of the SM WESS. No communications link to the locomotive is required.

A schematic of a possible control system is shown in Figure 10. The refrigeration plant is controlled by simple logic devices. Power flow at the utility and magnet voltage and current are sensed and inputted to the CPU of a microcomputer through A/D converters. The required control functions are implemented by software in the CPU, and control signals are outputted to the converter, inverter, persistent mode switch and external shunt switch.

7. ROUND TRIP EFFICIENCY

The round trip efficiency of the SM WESS is defined as:

$$\eta_{wess} = \frac{\text{energy returned to 50 kV line}}{\text{energy delivered from 50 kV line}} \times 100\%$$

The loss elements are indicated in Figure 11. To calculate the round trip efficiency, it is assumed that the SM WESS undergoes eight full charge/discharge cycles (i.e. from 7.5 kA to 15kA to 7.5 kA) per day, and that the charge or discharge time is 30 minutes.

Energy requirements and losses for the SM WESS are summarized in Table 5. Certain components, e.g. refrigeration for the magnet, are spread out over a full day. Each SM WESS cycle is therefore charged with one-eighth of this daily consumption.

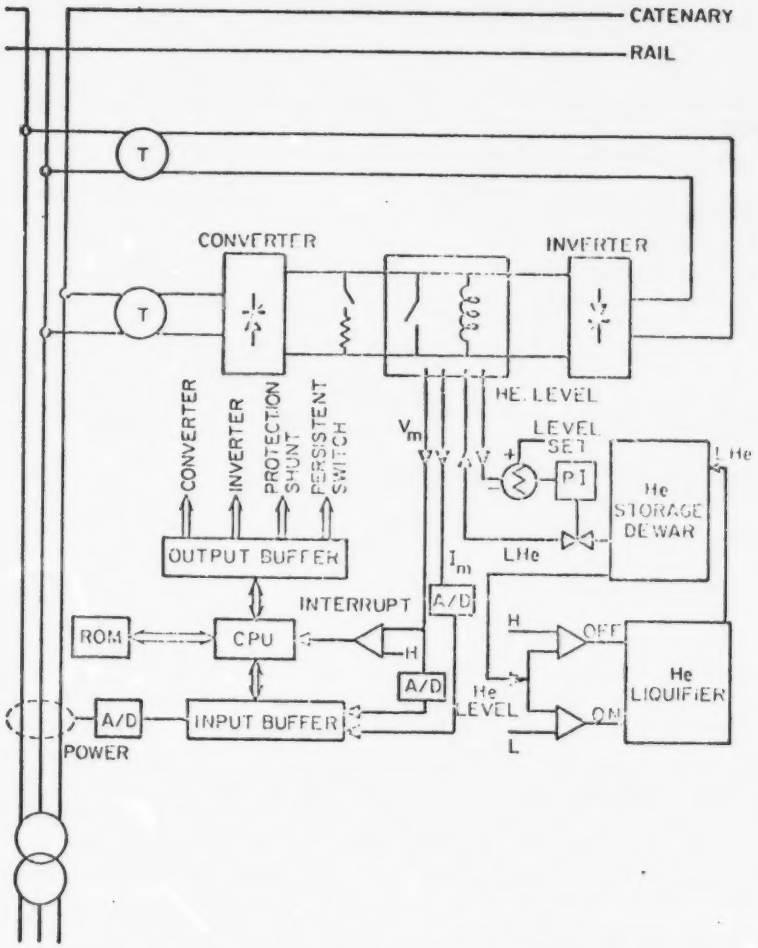

Figure 10 A schematic of the SM WESS control system

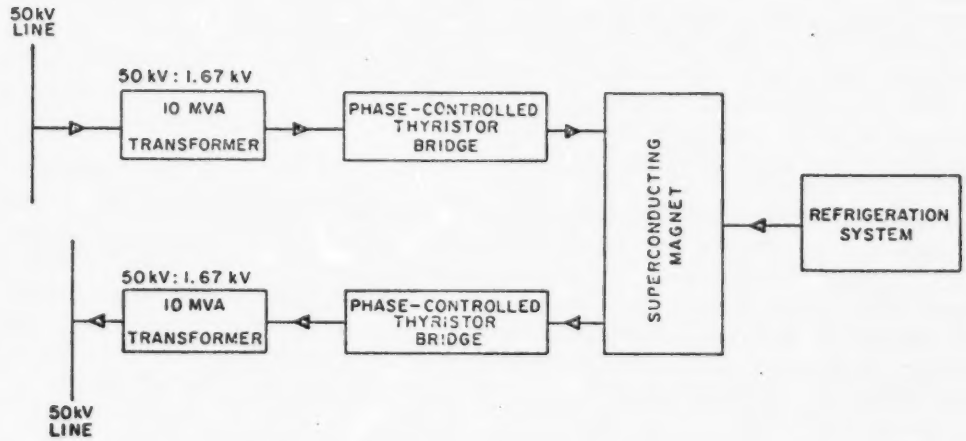

Figure 11 The principal loss elements in the SM WESS

TABLE 5 SM WESS ENERGY CONSUMPTION AND ROUND TRIP EFFICIENCY

Assumed number of round trips per day	8	
Energy Consumption per Cycle:		
Transformers; Core loss	0.43 GJ	
Copper loss	0.16 GJ	
Power Conditioners	0.28 GJ	
Refrigeration	2.11 GJ	
Other Plant Operations (pumping, control, etc.)	0.21 GJ	
TOTAL LOSS PER CYCLE		3.19 GJ
Usable Energy to be Stored in Coil		19.8 GJ
Energy that must be Delivered from 50 kV line		21.4 GJ
Energy that would be Returned to 50 kV line		18.2 GJ
ROUND TRIP EFFICIENCY		85%

The round-trip efficiency is calculated to be nominally 85 per cent. The dominant contribution to the inefficiency is clearly the energy requirement of the refrigeration system. A reduction of this component by a factor of two (by design modifications to the magnet and dewar structure, which would increase the capital cost) would improve the round-trip efficiency to 90 per cent. This is considered to be effectively the upper limit of system performance.

8. INITIAL AND OPERATING COSTS OF SM WESS

The initial cost of the superconductive wayside energy storage facility was evaluated by obtaining quotations for the limited number of standard components in the system and by developing cost estimates for the major components by discussion with various manufacturers and by reference to papers and to reports which discuss the economic aspects of railway electrification or proposed large-scale superconducting devices (e.g. fusion reactors and diurnal load levelling magnets).

The estimated SM WESS initial costs, from detail in reference 4, are summarized in Table 6. A 15 per cent engineering contingency has been added to the raw total of $28.8 million to give a final estimated total cost, in $1980, of $33.2 million. The uncertainty in this figure is considered to be ±$5 million. Clearly, the superconducting coil itself represents the major component (over 70 per cent) of initial cost.

In the discussion of the technical aspects of SM WESS, a number of alternatives were evaluated at various stages in the design, and particular concepts were selected for costing purposes. For

TABLE 6 INITIAL COSTS FOR THE SM WESS

	$1980 x 10^6
Site Acquisition and Preparation	1.82
External Structures and Buildings	1.33
Superconducting Coil	21.03 ± 4
Cryogenics	3.24
Electrical Equipment	1.41
Subtotal	28.83
15% Engineering Contingency	3.98
TOTAL	M$ 33.16 ± 5

example, 4.2 K pooling boiling and a fibre-reinforced-plastic dewar structure were selected over a 1.8 K supercritical helium system and stainless steel dewar. The economic impact of selecting the alternative concepts is likely to be within the costing uncertainty.

It is considered that $33.2(±5) million represents the best estimate of the initial cost of the SM WESS, based on the state-ofthe-technology or on reasonable short-term extrapolations of current trends. Operating costs, including electrical energy for refrigeration and services, personnel, maintenance and helium make-up are estimated to be $270 thousand per annum.

TABLE 7 EVALUATION OF ALTERNATIVE STORAGE CONCEPTS

Storage Concept	Round Trip Efficiency (%)	Installed $/kWh	Cycle Life	Service Life
Battery [3]	60	95	1,000	2 months
Pumped Hydroelectric [3]	76	1,356	10^6	30 years
Regeneration to Utility [3]	92	163	10^6	30 years
Compressed Air [3]	37	N/A	10^6	30 years
Flywheel [3]	91.2	370	10^6	30 years
Superconductive Magnet [4]	85 ±5	4,161	$>10^6$	30 years

9. CONCLUSIONS

One of the objectives of this project was to determine the technical feasibility of superconductive magnet wayside energy storage for implementation on Canadian railways. The system is, undoubtedly, technically feasible. The regenerative braking energy of loaded freight trains on down-grades can be stored, in a controllable manner, in the magnetic field of a large superconductive coil, and can subsequently be delivered to another train on an up-grade to limit the power demand from the utility.

While technically feasible, it must be noted that, in terms of its total stored energy (up to 26.4 GJ), the capacity of the required wayside energy storage magnet is 33 times larger than that of any superconducting magnet yet built. It is, however, a factor of 100-1,000 times smaller than magnets which are being proposed for utility diurnal load-levelling applications and on which significant engineering design has been conducted.[5,7] The SM WESS magnet could be built using techniques which are recognized as state-of-the-technology in the superconducting magnet industry or which represent modest extrapolations of current trends and developments in the industry.

The second objective of the project was to conduct an economic evaluation of SM WESS. The initial costs of $33.2 (± 5.0) million corresponds to an installed cost of 4,525 $/kWhr. For comparison, the installed costs and efficiencies for other storage systems as identified and evaluated by Garrett [2,3] are shown in Table 7.

The high initial cost of SM WESS leads to a return-on-investment, for implementation on the CRC and QNS&L railways, of less than 5 per-cent. It is evident that the high cost of superconducting coil (representing over 70 per cent of system cost) will prevent development of superconductive storage devices for railway applications, unless dramatic (but unlikely) cost reductions occur. It has therefore been recommended that no further work on the superconductive wayside energy storage system be conducted for Canadian freight railway applications.

This conclusion should not be interpreted to mean that any very large-scale superconducting storage device is unlikely to be economically viable. Research groups in Japan and the U.S. have shown that per-unit (e.g. per kWh) costs decrease as the scale of the magnet increases.[5,7] Superconducting magnets appear to be economically attractive for storage capacities in the range 1-10 GWh, as required for utility load levelling.

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